Global Energy Interconnection Development and Cooperation Organization

Vol. 1 No. 3 Aug. 2018
DOI: 10.14171/j.2096-5117.gei.2018.03.004

Global Energy Interconnection
www.geidco.org

Full-length article

Developing a global interconnected power system model

Maarten Brinkerink [1,2], Paul Deane [1,2], Seán Collins [1,2], Brian Ó Gallachóir [1,2]

1. MaREI Centre, Environmental Research Institute, University College Cork, 6 Lee Rd, Sunday's Well, Cork, T23 E4PW Ireland
2. School of Engineering, University College Cork, Cork, Ireland

Abstract: Decarbonizing the power sector is a necessary step towards a low-carbon future. Interconnecting power systems on different continents could be a method to contribute to such a future, by utilizing highly efficient renewable resources around the globe, while simultaneously providing additional benefits of power system integration. In this paper, we describe the process of constructing and simulating a global interconnected power system model with high technical and temporal resolution. Being the first of its kind on the global scale, this paper is designed to showcase the proof of concept as an intermediate step to a high resolution global model, by integrating an existing European power system model with the North-American continent. The work to date has been focused on testing the methodology and building up necessary knowledge to realistically simulate the functionality of a possible future global grid. Some initial results are analysed to support the viability of the model and the concept in general. Furthermore, key factors influencing the development and optimal performance of the global interconnected power system model are identified.

Keywords: Power system modelling, Dispatch modelling, Renewables, Global grid, Intercontinental interconnectors.

1 Introduction

Following the 2015 Paris Climate Change Agreement, ambitious climate mitigation targets have been set in place to pursue a goal of containing global average temperature increase to well below 2 degrees above pre-industrial levels, with a further aim to limit the increase to 1.5 degrees. Considering an increase in global future energy demand, as well as expected increasing shares of electricity in final energy consumption from below 20% today to between 23%-27% by 2040 [1], the power sector requires a drastic transition to a low-carbon future in response to said mitigation targets.

The theoretical potential of renewable electricity (RES-E) to decarbonize power systems is a well-documented aspect [2-4], yet the fluctuating characteristic in the generation of electricity from variable renewables (VRES) such as solar-PV systems and wind energy influences the practical implementation and reliability of power systems with increasing VRES penetration [5–10]. A common approach to handle the variability in generation is by interconnecting nearby power systems to cope with peaks and lows in non-dispatchable generation output. Other advantages of transmission interconnection relate to the provision of system security [11,12], possibility of cross-border trading and the integration of wholesale power markets [13], sharing of operating reserves [12,14] and accessibility to an overall more diverse, flexible and cost-efficient generation portfolio [12,15]. Technological progress in High Voltage Direct Current (HVDC) transmission has been significant in recent years [16–21]. Currently, ±800 kV land-based HVDC interconnectors with rated capacities of up to 8 GW exist in China, with even higher ratings of ±1100 kV and 12 GW to be reached in the near future [22]. Progress in submarine HVDC transmission projects occurs as well, albeit in smaller steps, for example with the commissioning of the EuroAsia interconnector, interconnecting Greece, Cyprus and Israel. Once completed, this 2GW, 1518 km long transmission link, will be the first (partial) submarine HVDC intercontinental interconnector [23]. Ardelean and

Received: 8 June 2018/ Accepted: 27 June 2018/ Published: 25 August 2018

Maarten Brinkerink
maarten.brinkerink@ucc.ie

Seán Collins
sean.collins@umail.ucc.ie

Paul Deane
jp.deane@ucc.ie

Brian Ó Gallachóir
b.ogallachoir@ucc.ie

Minnebo [16] conclude that submarine HVDC cables can now be considered a mature technology able to pay back the generally high investment costs.

A to date limitedly used application of transmission interconnection is the possibility to integrate the vast and highly efficient RES-E potential in distant and often unpopulated areas [24-26]. On a global scale, it's clear that there's an overall discrepancy between areas of high electricity consumption and areas with high RES-E potential [2,3,12,27,28]. The overall benefits of power system integration through transmission interconnection and the ability to utilize distant high RES-E resources are two core aspects underlying the concept of a globally interconnected power system[1].

In this article we describe the process of constructing and simulating a globally interconnected power system model as a proof of concept. An existing European power system model is interconnected to the North-American continent as an intermediate step to the global model, to test the methodology and for the purpose of knowledge building. Section 2 gives a short review on similar analyses done to date as an indicator of the necessity of this research. In section 3 we elaborate on the applied methodology for building the model. Section 4 includes an overview of lessons learned during early stages of the model building and highlights implications from modelling results. In the final section we discuss future work and the possibilities for engaging with the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) and its members.

2 Literature Review

To date, a number of studies have made efforts to simulate the global grid in a power system model. Although these studies show some potential benefits of power system integration towards the global grid, the relatively low nodal representation [29-32], low technological representation [29,33], limited locational data representation (e.g. lack of input data based on actual locational load- or VRES profiles outside Europe) [29,30,33] and the main focus on 100% RES modelling [29,30] impose a significant research gap surrounding the global grid concept.

In 1995, Dekker and colleagues [32] attempted to simulate a nine region interconnected global grid, yet the complexity of the optimization problem and the available modelling software limited the practical implementation at that time. No further research based on this model has been made public since. Biberacher [29] applied a linear least-cost optimization for the global grid with 11 nodes solely based on optimal utilization of available solar-PV and wind energy potential. They showed that in a scenario with large availability of low-cost storage, global interconnectors are primarily used to compensate for consistent geographical discrepancies in demand and supply. The high availability of storage made it more cost effective to store electricity locally in case of peak oversupply. In a scenario without storage, global interconnectors were used to handle short term variability in generation as well, but as Biberacher mentions "the grid becomes massively oversized". He furthermore indicates the compatibility of wind energy with a global grid due to the lower seasonal and diurnal variability compared to solar-VP, and a core flow of globally generated electricity (with Australia as main exporter) towards load centers in South-East Asia and China.

Aboumahboub and colleagues [30] applied a similar optimization methodology for a global grid model based on 51 nodes of equal geographical size, disregarding current borders of power systems and its associated generation portfolio's. The results showed that when comparing the optimization of an interconnected versus a non-interconnected scenario of the 51 regions, the overall required conventional backup capacity can be reduced by a factor of eight. This highlights the potential of smoothing global generation of VRES by utilizing seasonal and diurnal (time-zone differences) variability. Similar to [29], the authors highlight the importance of the duality of global interconnectors and regional storage, and also indicate the potential for South-East Asia, China and India to become main importers in the global grid context. In a follow-up study by the same authoring team [31], the importance of a global CO_2 price was reviewed in context of CO_2 abatement targets. When allowing the possibility of investment in interconnections between the 51 regions, a shift can be seen in the cost-optimal solution from high capacities of biomass- and gas-based generation to a increasing level of wind energy penetration to reach the same abatement targets.

By restricting the global supply of solar powered electricity generation at 2000 TWh by 2030 (approximately 7% of 2030 global demand), Ummel [33] attempts to apply a realistic limit on capacity expansion while optimizing the deployment of least-cost solar capacity around the globe. The author indicates "that there is generally low correlation of optimal generating sites and the location of electricity consumption", which from an intercontinental perspective results in significant flows through interconnections from the Middle-East and Northern-Africa (MENA) to Europe, the Persian-Gulf to India and from Australia to Indonesia.

1 Henceforth mentioned as global grid.

The modelling approach applied in this study is limited to the least-cost optimization of solar powered generation capacity, other parts of the power system, to supply the remaining 93% of 2030 demand, are not incorporated in the simulations.

3 Methodology

3.1 PLEXOS® Integrated Energy Model

To realistically simulate the operation of a potential future global grid, a unit commitment and economic dispatch methodology will be applied by means of the power system modelling tool PLEXOS® Integrated Energy Model [34]. The PLEXOS software is a market leader in large scale power and energy system optimisation and is freely available for academic research. XPRESS-MP is used as the solver. Unit commitment and economic dispatch within power systems refer to the optimal utilization of available power generation capacity to match system demand within the simulation period, while behaving in accordance with the technical constraints and limitations within said power system. The model optimises (using linear programming) the dispatch of thermal and renewable generation and pumped hydro storage. It does so subject to operational constraints at hourly resolution while holding the installed capacity constant. The model seeks to minimise the overall generation cost to meet demand, subject to the mix of installed generation fleets and their technical characteristics such as ramp rates, start costs, minimum up times etc. This includes operational costs consisting of fuel and carbon costs, and start-up costs consisting of a fuel offtake at start-up of a unit and a fixed unit start-up cost. In these day-ahead market simulations, a perfect market is assumed across the globe without consideration of market power or competitive bidding practices.

3.2 European electricity dispatch model

The starting point of developing the global grid power system model is an existing European electricity dispatch model with hourly temporal resolution (EU-28[1] + Norway and Switzerland) as constructed for previous work on the implications of the potential future European power system [10]. The European model (EU model) has been developed using a soft-linking approach to provide additional insights on the European Commission's EU 2016 Reference Scenario (EU-REF) [35]. The EU model consists of a single node per country. Furthermore, generator categories as constructed in PLEXOS® for the EU model, also follow EU-REF. A disaggregation approach has been used to convert aggregated overall capacities per power plant, per country, as given in EU-REF, into generator portfolios with standardized characteristics per generator unit. An overview of some of these characteristics can be found in Table 1. Localised hourly profiles for load and VRES are incorporated based on historical hourly data at country level. A carbon price of 88€/Tonne CO_2 is incorporated following EU-REF. For more details on the methodology and data assumptions behind the EU model we refer to [10].

Table 1 Sample of Standard Generator Characteristics.

Fuel Type	Capacity (MW)	Start Cost (€)	Min Stable Factor (%)
Biomass and Waste Fired	300	10000	30
Derived Gasses	150	12000	40
Geothermal Heat	70	3000	40
Hydro Lakes	150	0	0
Hydro Run of River (ROR)	200	0	0
Hydrogen	300	5000	40
Natural Gas CCGT	450	80000	40
Natural Gas OCGT	100	10000	20
Nuclear Energy	1200	120000	60
Oil Fired	400	75000	40
Coal Fired[1]	300	80000	30

[1] *Also includes lignite-based capacity.*

3.3 Connecting the Continents

As a proof of concept, the existing EU model has been expanded and interconnected to a combined European - North American (NAM, consisting of Canada and the United States) power system model for the 2050 reference scenario. The purpose of this intermediate step towards a globally interconnected power system model is to validate the functionality of the applied methodology and to build up relevant knowledge and experience. Thus, potential limitations can be identified in an early stage and can be regarded as lessons for the larger project resulting in an overall more efficient process. North America was chosen due to the availability of generally open access power system data, especially compared to other regions of the world.

The EU model consists of 30 nodal regions (one per

1 Including the United Kingdom as representing the EU to date.

country) in total. The NAM model has been constructed based on a relatively similar sized nodal representation with 20 nodes in the United States (US) following the identified regions within the National Energy Modelling System (NEMS, three New York NEMS regions combined into a single node) as used for the annual energy outlook (AEO) by the U.S. Energy Information Administration (EIA) [36,37], and eight nodes in Canada composing of the grid-connected provinces of Alberta, British Columbia, Manitoba, Newfoundland and Labrador, Ontario, Quebec, Saskatchewan and a combined node of the remaining Atlantic regions. Fig. 1 shows an overview of the nodes in the combined model, together with the relative demand per node for the 2050 reference case.

The 2050 generator portfolio for the US, nodal fuel pricing and total demand are based on the reference scenario of the 2017 AEO of the EIA [37,38]. Compared to Europe, fuel prices in the AEO for coal and gas are significantly lower. An overview of fuel and carbon pricing for all regions can be seen in Table 2. Load profiles for different US nodes are developed by combining and scaling historical (mostly 2015) load profiles of the relevant balancing authorities (BA) within each node, as retrieved from the Federal Energy Regulatory Commission (FERC) [39]. BA's per node have been identified based on geographical visualizations from the EIA and FERC [40,41], and individual market reports of the BA's. For this study it has been assumed that peak loads per node scale linearly with the overall increase in load between 2015 and 2050. Due to a lack of available transmission capacity data for the US, net transfer capacities (NTC) between nodes have been determined by assuming that the maximum hourly flow between BAs during 2015 and 2016, as retrieved through EIA's data plugin [42], can be seen as representative.

The reference scenario for the Canadian nodes is based on the projected energy future by the National Energy Board of Canada [43]. The projected future runs until 2040, hence for the purpose of this study, the trends for factors such as generator portfolio's, overall demand per node and fuel prices have been extrapolated to 2050. Contrary to the US in the AEO, carbon pricing is introduced in the projected energy future scaling to C$50/Tonne CO_2 by 2022 (€32.8/Tonne CO_2, €1 - C$ 1.525) and remaining steady afterwards, equaling an inflation adjusted carbon price of €18/Tonne CO_2 by 2050.

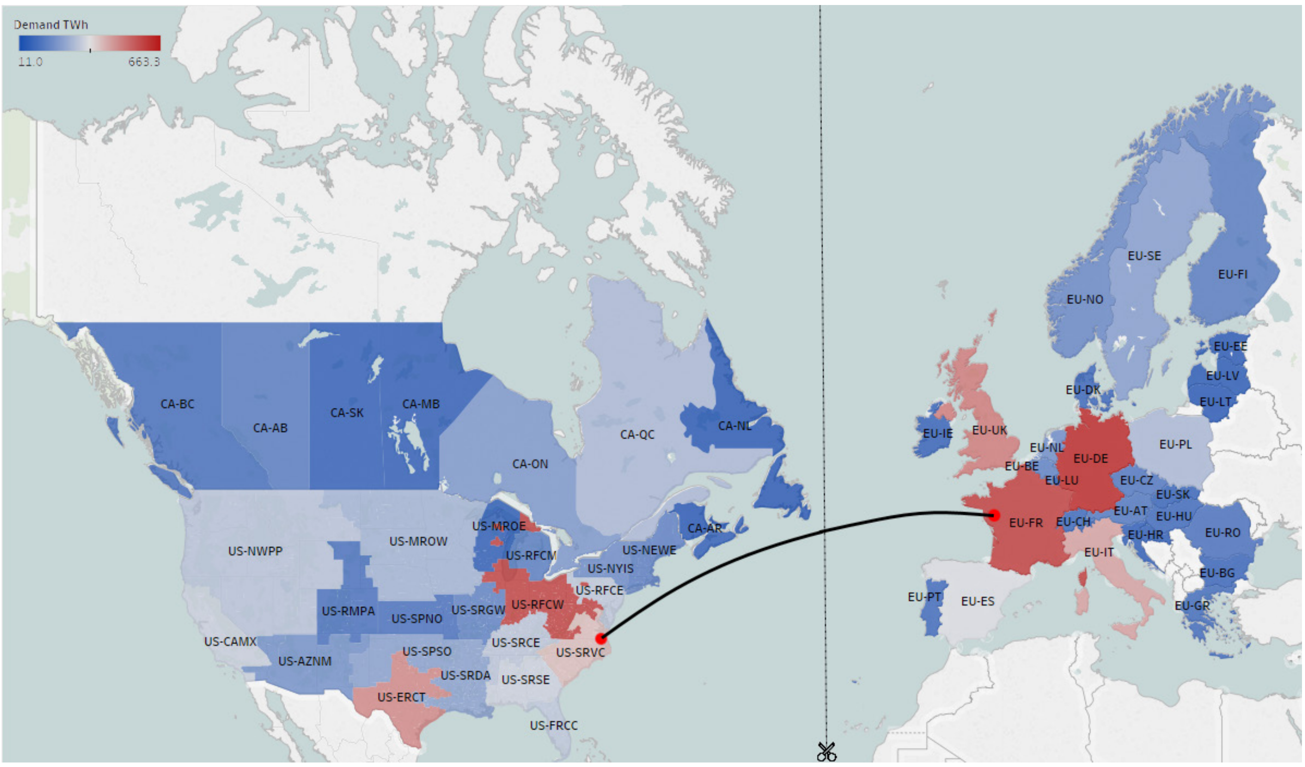

Fig. 1 Nodal representation of the combined 2050 EU-NAM power system model. Relative demand per node is showcased by a colour scheme ranging from dark blue (EU-LT 11 TWh) to dark red (EU-DE 663 TWh). The map is cropped horizontally for visibility reasoning, the interconnector between EU-FR and US-SRVC stretches approximately 6000 km. Red sections in US-MROE are part of balancing authorities in US-RFCW.

Table 2 Overview fuel- and carbon pricing per region for the 2050 reference model. Applied exchange rate of €1 – US$1.16 and €1 – CA$1.525.

Region/Node	Coal price (€/GJ)	Gas price (€/GJ)	Oil price (€/GJ)	Carbon price (€/Tonne)
Canada	2.49	3.71	11.77	18
Europe	4.1	11.08	18.5	88
US-CAMX[1]	2.24	5.38	22.93	0
US-ERCT[1]	2.19	5.34	20.90	0
US-RFCW[1]	2.15	5.74	22.30	0
US-SRSE[1]	2.49	5.35	21.99	0
US-SRVC[1]	2.75	5.70	18.47	0

[1] The AEO incorporates region specific fuel prices for the different US regions depending on accessibility to fuels and regional policies. Pricing for other US nodes fall within the range of the above sample.

Historical hourly load profiles for the different nodes are retrieved from the relevant system operators through online data portals [44–48] and personal communication (L. St-Laurent, Hydro Quebec, 12-02-2018 – B. Owen, Manitoba Hydro, 01-12-2017 – R. Mall, SaskPower, 21-12-2017), and scaled to expected 2050 values. Gas and oil fuel prices are based on the NEB, yet coal prices are not included in the study. Hence to retain uniformity, an averaged coal fuel price based on the AEO is incorporated for the Canadian nodes. Interregional transmission capacities and cross-border transmission capacities towards the US are retrieved from the market reports of the Canadian system operators. For the purpose of testing the methodology in the 2050 reference scenario, a uniform increase of 25% of NTC has been applied for all existing transmission pathways between nodes in North America compared to the reference 2015 values.

Localised hourly wind and solar profiles for the North American nodes are retrieved from the Renewables Ninja database [49,50] (https://www.renewables.ninja/). A single locational sample pattern per node for the 2015 meteorological year is taken to capture the diversity in profiles. A more detailed approach will be applied in a later stage to incorporate geographical differences within nodal regions. All hourly profiles, both for VRES as well as load, have been centred around UCT. This means that the first hourly timestep is set at UCT 12 AM and all profiles shifted accordingly depending on the longitudinal time-zone differences.

For this proof of concept study, the European and North American systems are interconnected by a 5 GW intercontinental interconnection linking the EU-FR and US-SRVC nodes, as shown in figure 1. These nodes are chosen due to their geographical location, relatively large size (demand and installed capacity) and its significant interconnectivities to other nodes in the continents. These factors influence the possibility for trade. Incremental losses of 15% for transmission and conversion are applied on the interconnection, assuming a near 6000 km transmission distance, as well as wheeling charges of €4/MWh.

4 Preliminary results and lessons learned

This section showcases some early stage results of the possible functionality of a transcontinental interconnector between Europe and North America. It furthermore highlights the experiences to date regarding the development of a global interconnected power system model. By no means are these early stage results definitive, they are incorporated to support the proof of concept.

4.1 Europe – North America interconnector utilization

Due to the longitudinal direction of the interconnector, multiple time-zones are covered when bridging the continents. This affects the match in absolute time of occurrence of factors such as peaks in load and variable generations (especially solar-PV). An example of this is visualized in Fig. 2, showcasing the load profiles of

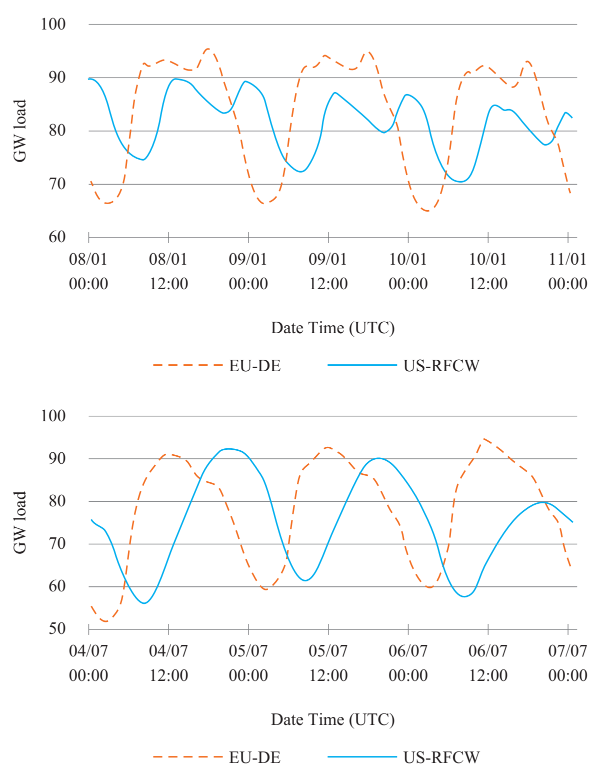

Fig. 2 Impact of longitudinal time-zone differences on match in load profiles between EU-DE (UTC +1) and US-RFCW (UTC−5) during three days in January (Top) and July (bottom)

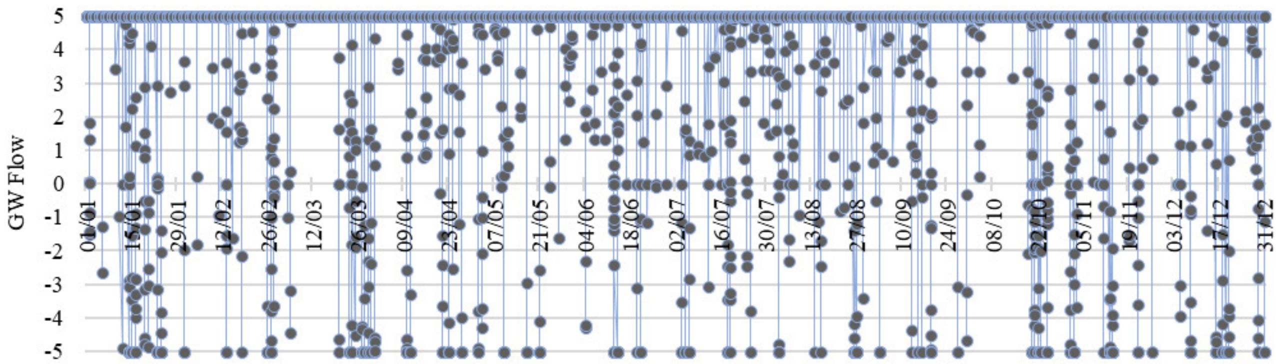

Fig. 3 Hourly utilization of the 5 GW EU-NAM interconnector in the 2050 reference model. Positive flow is in the European direction, negative flow is in the North American direction

Germany (EU-DE) and US-RFCW as the nodes with the highest demand in 2050 in both continents (EU-DE 663 TWh, US-RFCW 608 TWh). The six-hour time-zone difference between both nodes causes peaks in demand to occur on different timesteps during the diurnal cycles. The graph shows that in some cases, peaks in one continent partially coincide with off-peak hours on the other continent. This indicates the potential benefit of utilizing intercontinental interconnectors for trade by dispatching low-cost generators on either side of the link, especially considering the total time-zone span of between UTC +2 in Eastern Europe and UTC −8 at the west coast of North America.

The utilization of the EU-NAM interconnector within the context of this study is visualized in Fig. 3. The vast majority of flow in the 2050 reference scenario is oriented towards Europe, with a total flow of 39.2 TWh in the European direction and only 2.5 TWh towards North America. Overall, the interconnector has a capacity factor (CF) of just above 95.3% with occurrence of full load hours (FLH) during 91.8% of the year. Due to the almost constant transmission congestion, impact of the interconnector on balancing market prices between both nodes (and continents) is limited. The high utilization of the interconnector all year round indicates that the impact of diurnal or seasonal variability on the size of flow is limited. The main driver for the flow towards Europe can be allocated to the significantly lower short run marginal costs (SRMC) for thermal based generation capacity in North America, mostly due to lower applied fuel and carbon pricing compared to Europe as indicated in Table 2. Combined Cycle Gas Turbines (CCGT) and coal power plants in North America are often dispatched before similar plants in Europe to supply the European market. To assess the sensitivity of these elements, multiple alternative scenarios are simulated with incremental carbon prices for North America, gradually increasing towards European levels. The results can be seen in Fig. 4.

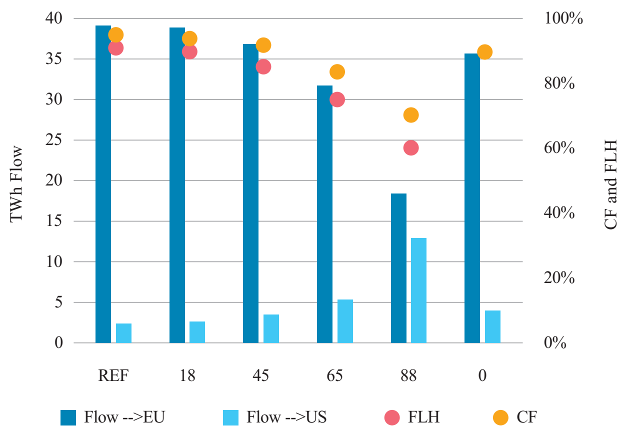

Fig. 4 Interconnector utilization under different carbon price assumptions. Scenario names are based on applied carbon pricing in North America per scenario; REF (EU €88/Tonne CO_2, CA €18/Tonne CO_2, US €0/Tonne CO_2), 18 (EU 88, NAM 18), 45 (EU 88, NAM 45), 65 (EU 88, NAM 65), 88 (EU 88, NAM 88), 0 (EU 0, NAM 0).

Based on this graph several important observations can be made. Firstly, the incremental carbon price has limited impact on the flow direction when compared to the REF scenario, until it reaches €88/Tonne CO_2 in both continents. Overall utilization of the interconnector decreases with increasing carbon prices in North America, due to lower price differentials in SRMC between power plants on both continents. The significant increase in export towards North America in the €88/Tonne CO_2 scenario results from displacement of coal fired power plants (coal and lignite) and open cycle gas turbines (OCGT) in North America in favor of CCGTs in Europe following a shift in the merit order of the combined market. When carbon pricing is omitted from the model, as shown in the €0/Tonne CO_2 scenario, the majority of flow remains oriented towards Europe. Considering the setup of power plant portfolios in both continents, as shown in table A1 in the appendix, with Europe incorporating significantly higher penetration of VRES, this is counter-intuitive. It indicates that carbon pricing is not the only impacting factor in this reference scenario, but that also the differences in baseload (US much more coal capacity) and differences in fuel pricing are of paramount importance. The impact of fuel pricing on the interconnector utilization is visualized in Fig. 5, where the original scenarios as assessed in Fig. 4 (REF, 0 and 88) are compared to scenarios with similar carbon pricing but with standardized fuel prices for all regions based on the reference EU fuel prices.

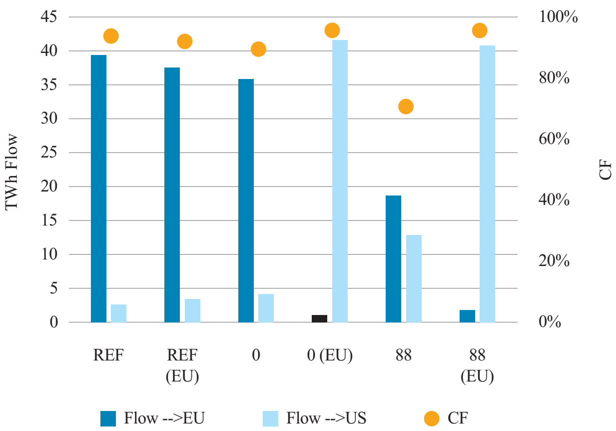

Fig. 5 Interconnector utilization under different fuel and carbon price assumptions. REF, 0 and 88 scenarios incorporate incremental carbon pricing with reference continental (or nodal in case of US) specific fuel pricing following table 2. REF (EU), 0 (EU) and 88 (EU) scenarios incorporate incremental carbon pricing with standardized fuel pricing based on the reference European fuel prices.

The flow dynamics on the interconnector within the REF scenario with standardized European fuel prices (REF (EU)) are relatively similar to the baseline REF scenario. Although the differences in SMRC's on both continents are reduced, the lack of carbon pricing in the US alone remains sufficient to cost-efficiently supply the European market. Yet, when considering scenarios with equal carbon pricing and equal standardized fuel prices (0 (EU) and 88 (EU)) the market situation changes drastically. The interconnector in both scenarios is almost fully utilized for trade in the direction of North America, with total yearly unidirectional flows of around 41 TWh. Overall interconnector CF's of above 97% are reached. The main reason for the consistent flow towards North America relates to the relatively high penetration of RES-E in Europe and the strong interconnectivity between European countries which allows for coordinated export of low carbon power. Within the 88 (EU) scenario, the RES-E capacity in Europe is able to supply 1345 TWh for the total 2050 demand of 4237 TWh (31.7% RES-E penetration), whereas the RES-E capacity in NA is limited to a supply of 860 TWh for the total 2050 demand of 5373 TWh (16% RES-E penetration). The higher RES-E penetration in Europe allows for dispatch of cost-efficient unused thermal capacity for export purposes towards North America. Depending on the carbon pricing, this can either be CCGT capacity or coal fired, next to available nuclear baseload in EU-FR during periods of high VRES generation. From a North American viewpoint, the RES-E capacity in North America in this reference model is not sufficient to stimulate bidirectional utilization of the interconnector by making use of seasonal- or diurnal time-zone differences. That said, the high overall CF do indicate that there is potential for an EU-NAM interconnector. This is supported by findings in other studies [25,51]. Determining the market revenues and investment costs would be the next step to assess the viability in more detail.

This section shows the sensitivity of market elements on intercontinental interconnector utilization. Yet it is safe to say that the indicated unilateral export of emission intensive power from the US towards Europe in the reference scenario, without appropriate carbon pricing, would never be acceptable in a real market environment. The sensitivity and importance of clear market rules for interconnecting different regions are commonly raised points of interest, especially in context of intercontinental interconnectors and the global grid concept [14,28,52,53].

For further development of the global interconnected model, it is crucial to assess the functionality and economic utility of the global grid in a variety of possible future pathways of the power systems worldwide. This will be captured by constructing a global reference model based on current policies and developments, as well as a variety of realistic mitigation scenarios.

4.2 Data availability

The decision to initially use a combined EU-NAM power system model as an intermediate step towards the global model is due to the availability of detailed power system data for both continents. To expand the model further to the global scale, a combination of approaches to retrieve necessary data must be utilized, since open-access data for other regions in the world is not always available.

Hourly load data can in some cases be accessed through data portals of representative system operators (e.g. Australia [54], Japan [55], Mexico [56] and Russia [57]). Secondly, it might be possible to retrieve profiles from system operators through personal communication, as has been done for this study for some of the Canadian provinces. Yet, it is unlikely that this is accomplishable for all regions in the world since it's a time-intensive process. Furthermore, operators are not always willing to make data publicly accessible. An alternative approach would be to make use of existing profiles of relatively similar regions (e.g. similar sectoral demand distribution or similar climate zone) by shifting and scaling the profiles based on time-zone, total demand and possibly peak demand if available. This is a commonly used approach in global power system studies [29,30], yet it does limit the accuracy of locational representation. Decisions regarding the approach will be made by balancing time-intensity and data accuracy. Hourly profiles for VRES will be developed by utilizing historical locational profiles from the Renewables Ninja database [49,50] (https://www.renewables.ninja/). Samples will be taken based on a raster approach with fixed dimensions (e.g. 100 x 100 km) and aggregated to incorporate regional differences within nodal regions. Profiles will be scaled based on prospects for technology efficiency, impacting the hourly capacity factors.

Generation portfolios for 2050 global grid reference and mitigation scenarios could potentially be developed through two methods. The first approach would be to make use of existing scenario studies as developed for different regions in the world, with the AEO, EU-REF and the NEB energy futures as exemplary studies. Yet, this has two disadvantages. Firstly, it is difficult to accurately combine data from multiple studies into one aggregated scenario, since assumptions behind the different studies are rarely in line. For example, portfolios in the studies are often optimized based on different emission reduction targets, or different assumptions are incorporated on global learning curves for generation technologies, impacting the cost-optimal capacity expansion per study in a different fashion. Furthermore, existing studies have not incorporated the possibility of power exchange between continents or accessing remote RES-E through global interconnectors. Hence, applied capacity expansions in these studies are not optimized in the context of the global grid concept. An alternative approach would be to make use of the capacity expansion function within PLEXOS®. Performing optimizations in the global grid context in PLEXOS®, by allowing capacity expansion of intercontinental interconnectors and RES-E capacity in distant areas, could overcome the described issues. For this approach a baseline reference model is required as a starting point for the capacity expansion. The recently published global database of power plants initiated by the World Resources Institute (WRI) and partners would be an important background source for this approach [58]. The database currently covers 62% of global installed capacity at unit level, with expected expansion to over 85% in the near future. The capacity at unit level can be manually aggregated based on the chosen nodal representation for the global model and integrated with the previously constructed 2015 European and North American reference models in PLEXOS®.

Final aspect to consider is input data for the existing power grid. Power system operators are often protective of grid data, mostly for security reasons, yet also because grid data could give insights in operator revenues through power system modelling which is regarded as sensitive information [59]. Approaches to recreate transmission capacities between nodes as used for the NAM model (using hourly exchange values or market reports) are of limited applicability for other regions of the world. As an alternative, open-access grid databases such as OpenStreetMap (openstreetmap.org) can be utilized to retrieve voltage data for interconnections between nodes. The voltage data can then be converted into NTC by applying a standardized conversion based on voltage size and transmission type (AC or DC). Although the final NTC's will be simplified, it can act as a baseline for the 2050 power grid. Recently, Liang [60] introduced an initiative focused on the construction of a global database with detailed grid and generation capacity data for over 140 countries in six continents. In time, this could potentially become an important source by linking the database with the global grid model in PLEXOS®.

4.3 Computational time (CT)

In earlier studies for which global grid models were utilized, the computational time of these models has been identified as a limiting factor because of the mere size and complexity of the unit commitment and dispatch problem [29,32]. Yet, developments in hardware, software and solver since these studies, allow for significant reductions in computational time for similar sized problems. Table 3 shows an overview of total computational time for a variety of scenario runs for the interconnected 2050 reference model with different unit commitment optimality's - determining how integers are treated in the unit commitment - and deviating complexity of the power system.

Table 3 Computational time in hours (CT) for multiple scenario runs in the interconnected 2050 reference model. Simulations performed with a Dell laptop (I5 processor, 8 GB RAM, 256 GB SSD) and with Xpress-MP. Results showcase CT for the full 2050 year with hourly timesteps (8760 in total).

2050 REF Detailed[1]	CT (hours) Constrained flow[2]	CT (hours) Unconstrained flow
MIP[3]	27	25.2
RR[4]	5	4.8
LP[5]	4.2	3.4

continue

2050 REF Simplified	CT (hours) Constrained flow[2]	CT (hours) Unconstrained flow
MIP[3]	14	11.8
RR[4]	1.1	1
LP[5]	0.8	0.6

[1] *Includes Pumped Hydro Storage (PHS) and multiple start states for CCGT's in the simulation.*
[2] *Flow between EU-FR and US-SRVC through the EU-NA interconnector is constrained at 5 GW.*
[3] *Mixed Integer Programming.*
[4] *Rounded Relaxation.*
[5] *Linear Programming.*

Depending on the complexity of the problem and the chosen unit commitment optimality, the CT ranges from below an hour to more than a day. Initial scenario runs while building and testing the global grid model, as also done for this article, will be done with limited complexity and rounded relaxation (RR) to limit the CT. Mixed Integer Programming (MIP) will only be applied in runs when quantification of final results is of importance. A CT of 27 hours for a two-continent model is acceptable for now. Yet, when the model will be expanded to the global context, simulations might potentially be performed on a high-performance computer or cloud limiting the required CT. Overall, limitations as a result of CT in context of the development and utilization of the global grid model are expected to be of modest impact.

5 Discussion and future work

The purpose of this paper has been to introduce the process of developing and simulating a global interconnected power system model as a proof of concept. The work to date has been focused on testing the methodology and building up necessary knowledge to realistically simulate the functionality of a possible future global grid. Some initial results have been analysed to support the viability of the model and the potential concept in general. Furthermore, key factors influencing the development of the global interconnected power system model are identified, as well as factors influencing the optimal performance of said model in PLEXOS®.

Going forward, several steps must be taken to construct a usable global model to assess the functionality and (economic) utility of a global grid. Firstly, decisions must be made regarding the methodology for retrieving input data as well as on the spatial resolution for the different continents. A balance will be sought between time intensity and data accuracy. After that, in parallel with retrieving the input data, an unpopulated model for all continents needs to be constructed based on the template of the European and North American models. Once the empty model is created and the input data is retrieved, the model can be populated. A global reference model based on current policies and developments will be developed, as well as a variety of realistic mitigation scenarios to assess a global grid in a variety of potential future pathways.

The Global Energy Interconnection Development and Cooperation Organization (GEIDCO) consists of a broad range of member experts from academia, industry and other associations. Within this community, considerable knowledge and data regarding the power system and power grid (e.g. [60]) for areas outside Europe and North America should be available. For the purpose of constructing the global model this experience could potentially be utilized, hence active engagement and collaboration with GEIDCO and its members is being sought.

Acknowledgements

This work was supported by Energy Exemplar and Science Foundation Ireland (SFI) MaREI centre (12/RC/2302).

Appendix A PLEXOS Detailed Equations

Indices

j	Generation Unit
t	Time Period
stor	Index related specifically to pumped storage unit
RES^{up}	Upper Storage Reservoir
RES_{low}	Lower storage Reservoir

Variables

V_{jt}	Integer on/off decision variable for unit j at period t
X_{jt}	Integer on/off decision variable for pumped storage pumping unit j at period t
U_{jt}	Variable that = 1 at period t if unit j has started in previous period else 0
P_{jt}	Power output of unit j (MW)
H_{jt}	Pump load for unit j period t (MW)
W_{int}	Flow into reservoir at time t (MWh)
W_{outt}	Flow out of reservoir at time t (MWh)
W_t	Volume of storage at a time t (MWh)

Parameters

vl	Penalty for loss of load (€/MWh)
vs	Penalty for Reserve not met
use	Unserved Energy (MWh)
usr	Reserve not met (MWh)
D	Demand (MW)
obj	Objective Function
n_{jt}	No load cost unit j in period t (€)

c_{jt}	Start cost unit j in period t (€)
m_{jt}	Production Cost unit j in period t (€)
e_{stor}	Efficiency of pumping unit (%)
$pmax_j$	Max power output of a unit j (MW)
$pmin_j$	Mini stable generation of unit j (MW)
$pmpmax_{stor}$	Max pumping capacity of pumping unit
J_j	Available units in each generator
J_{stor}	Number of pumping units
MRU_j	Maximum ramp up rate (MW/min)
MRD_j	Maximum ramp down rate (MW/min)
MUT_j	Minimum up time (hrs)
A_p	Number of hours a unit must initially be online due to its MUT constraint (hrs)
W_{INT}	Initial Volume of reservoir (GWh)
W	Maximum volume of storage (GWH)

Objective Function:

$$OBJ = Min \sum \sum_{t \in T} c_{jt}.U_{jt} + n_{jt}.V_{jt} + m_{jt}.P_{jt} + vl.use_t + vs.usr_t \quad (1)$$

The objective function in PLEXOS is to minimise the start-up cost of each unit (start cost (€)* number of starts of a unit) + the no load cost of each online unit + production costs of each online unit + the penalty for unserved load+ the penalty of unserved reserve. The objective function is minimised within each simulation period. The simulation solution must also satisfy the constraints below:

Energy Balance Equation:

$$\sum \sum_{t \in T} P_{jt} - H_{jt} + use_t = D_t \quad (2)$$

Energy balance equation states that the power output from each unit at each interval minus the pump load from pumped storage units for each interval + unserved energy must equal the demand for power at each interval. (Note that line losses can also be included here but is not shown). As the penalty for unserved energy is high and part of the objective function, the model will generally try to meet demand.

Operation Constraints on Units:

Basic operational constraints that limit the operation and flexibility of units such as maximum generation, minimum stable generation, minimum up/down times and ramp rates.

$$-V_{jt} + U_{jt} \geqslant -1 \qquad \forall t = 1 \quad (3)$$

$$V_{jt} - V_{jt+1} + U_{jt+1} \geqslant 0 \quad (4)$$

These two equations define the start definition of each unit and are used to track the on/off status of units.

$$P_{jt} - P\max_j .V_{jt} \leqslant 0 \quad (5)$$

Max Export Capacity: A units power output cannot be greater than it maximum export capacity.

$$P_{jt} - P\min_j .V_{jt} \geqslant 0 \quad (6)$$

Minimum Stable Generation: A units output must be greater than it minimum stable generation when the unit is online.

$$H_{jt} - Pmp\max_{Stor} .X_{jt} \leqslant 0 \quad (7)$$

Pumping load must be less than maximum pumping capacity for each pumping unit

$$V_{jt} + X_{jt} \leqslant 1 \text{ where } j \in stor \quad (8)$$

$$V_j \leqslant J_j \quad X_j \leqslant J_{Stor} \quad j \in J \quad (9)$$

These constraints limit a pumped storage unit from pumping and generating at same time.

$$A_{p,j} \geqslant V_{j,t} - V_{j,t-1} \forall t..t - MUT_j - 1 \quad (10)$$

$$V_{j,t} \geqslant A_{p,j} - \sum_{t}^{t-MUT_j+1} V_{j,t} / MUT_j \forall t \quad (11)$$

Minimum Up Times[1]: (Note the following text is directly from the PLEXOS Help files). The variable A_p tracks if any starts have occurred on the unit inside the periods preceding *p* with a window equal to MUT. *i.e.* if no starts happen in the last MUT periods then A_p will be zero, but if one (or more) starts have occurred then A_p will equal unity. The MUT constraints then set a lower bound on the unit commitment that is normally below zero, but when a unit is started, the bound rises above zero until the minimum up time has expired. This fractional lower bound when considered in an integer program forces the unit to stay on for its minimum up time.

$$A_{p,j} \geqslant V_{j,t-1} - V_{j,t} \forall t..t - MDT_j + 1 \quad (12)$$

$$V_{j,t} \leqslant 1 + \sum_{t}^{t-MDT_j+1} V_{j,t} / MDT_j - A_{p,j} \forall t \quad (13)$$

Minimum Down Times: The variable A_p tracks if any units have been shut down inside the periods preceding *p* with a window equal to MDT. *i.e.* if no units are shut down in the last MDT periods then A_p will be zero, but if one (or more) shutdown then A_p will equal unity. The MDT constraints then set an upper bound on the unit commitment that is normally above unity, but when a unit is stopped, the bound falls below unity until the minimum down time has

1 PLEXOS Help Files

expired.

$$P_{\mathrm{jt}} - P_{\mathrm{j.t-1}} - MRU_{\mathrm{j}}.V_{\mathrm{jt}} - p_{\min\mathrm{j}}.U_{\mathrm{j}} \leqslant 0 \quad (14)$$

$$p_{\min\mathrm{j}}.P_{\mathrm{jt}} + P_{\mathrm{jt}} - P_{\mathrm{j.t-1}} - P_{\mathrm{jt}}.(MRD_{\mathrm{j}} - p_{\min\mathrm{j}}) \leqslant 0 \quad (15)$$

Maximum Ramp up and down constraints: These constraints limit the change in power output from one time period to another.

Water Balance Equations:

These equations track the passage of water from the lower reservoir to the upper reservoir. In this set-up there is no inflow and water volume is conserved.

$$W_{\mathrm{tR}} + W_{\mathrm{out.tR}} - W_{\mathrm{in.tR}} = W_{\mathrm{INT,R}} \quad \forall t = 1, R \in RES_{\mathrm{Up}}, RES_{\mathrm{low}} \quad (16)$$

$$W_{\mathrm{t.RES}^{up}} + W_{\mathrm{out,RES}^{up}} - W_{\mathrm{in,RES}^{up}} = 0 \quad (17)$$

$$e_{\mathrm{stor}}.H_{\mathrm{jt.RES}^{up}} - W_{\mathrm{in.tRES}^{up}} = 0 \quad (18)$$

$$P_{\mathrm{stor.t}} - W_{\mathrm{out.t.RES}^{up}} = 0 \quad (19)$$

Appendix B

Table B1 Installed capacities (MW) and total load (TWh) 2050 EU-NAM reference model. 'Other' nodes are aggregations of the remaining nodes in the respective country or continent.

Node	Hydro[1]	Solar[2]	Wind Offshore	Wind Onshore	Other RES[3]	NG CCGT	NG OCGT	Nuclear	Oil	Coal Fired[4]	Load (TWh)
EU	*189513*	*295194*	*47448*	*319081*	*62837*	*241726*	*29131*	*96199*	*3367*	*55210*	*4237*
EU-DE	7170	86141	9369	77180	6756	36754	4672	0	674	24057	663
EU-ES	17158	49359	153	46989	2153	12965	1517	0	782	97	333
EU-FR	26559	45200	6056	51513	6468	30812	4112	32276	625	2892	617
EU-IT	19588	56765	644	25314	6806	40549	4513	0	128	1901	438
EU-UK	1818	11255	16533	24935	18163	41457	4645	17302	339	448	502
EU 'Other'	117220	46475	14693	93150	22492	79189	9673	46621	818	25815	1694
CA	*92260*	*7131*	*0*	*27508*	*4714*	*31345*	*11999*	*9838*	*2485*	*1172*	*705*
CA-AB	913	368	0	7347	695	16576	6217	0	7	0	107
CA-ON	9978	5916	0	7224	1308	8789	3698	9133	294	0	175
CA-QC	43289	355	0	6781	671	560	31	0	159	0	251
CA 'Other'	38079	491	0	6156	2039	5420	2052	705	2025	1172	171
US	*80902*	*148026*	*29*	*186296*	*16274*	*374400*	*213024*	*76500*	*8091*	*159781*	*4669*
US-CAMX	10105	10343	0	21402	6387	16756	12204	0	100	33	295
US-ERCT	457	2031	0	23375	266	64334	32630	4628	27	9891	280
US-RFCW	1638	7350	0	24587	435	38811	27592	10568	456	30300	608
US-SRSE	3760	23370	0	15	210	27627	8919	6942	277	9259	301
US-SRVC	3590	27775	0	1001	914	31858	11573	14686	685	9440	394
US 'Other'	61353	77156	29	115916	8062	195014	120105	39675	6547	100859	2791

[1] *Includes hydro impoundment and hydro run of river, pumped hydro storage not incorporated in early-stage simulations.*
[2] *Includes concentrated solar power and solar-PV.*
[3] *Includes biomass and waste, geothermal, tidal and wave-based capacity.*
[4] *Also includes lignite-based capacity.*

References

[1] IEA (2017) World Energy Outlook 2017, Paris

[2] Deng Y, Haigh M, Pouwels W et al (2015) Quantifying a realistic, worldwide wind and solar electricity supply. Global Environmental Change, Vol. 31, pp: 239-252

[3] Edenhofer O, Pichs Madruga R, Sokona Y et al (2012) Renewable Energy Sources and Climate Change Mitigation (Special Report of the Intergovernmental Panel on Climate Change). Cambridge University Press, Cambridge

[4] Jacobson MZ, Delucchi MA, Bauer ZAF et al (2017) 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 1(1):108-121

[5] de Boer HS, van Vuuren D (2017) Representation of variable renewable energy sources in TIMER, an aggregated energy system simulation model. Energy Economics Vol. 64, pp: 600-611

[6] Denholm P, Margolis RM (2007) Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy Policy 35(5): 2852-2861

[7] Cochran J, Bird L, Heeter J et al (2012) Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience, Summary for Policymakers, Golden, Colorado

[8] Pierre I, Bauer F, Blasko R et al (2011) Flexible generation: Backing up renewables, Brussels

[9] Ulbig A, Borsche TS, Andersson G (2014) Impact of low rotational inertia on power system stability and operation. In: Proceedings of the 19th World Congress The International Federation of Automatic Control Cape Town, South Africa. August 24-29, 2014. IFAC, pp: 7290-7297

[10] Collins S, Deane JP, Ó Gallachóir B (2017) Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model. Energy 130(1): 433-447

[11] Robinson D (2017) Economic and Geopolitical Determinants of Trade in Electricity. In: International Trade in Sustainable Electricity; Regulatory Challenges in International Economic Law. Cambridge University Press, Cambridge, pp: 54-73

[12] IEC (2017) Global Energy Interconnection. Geneva

[13] Bompard E, Fulli G, Ardelean M et al (2014) It's a Bird, It's a Plane, It's a … Supergrid!; Evolution, Opportunities, and Critical Issues for Pan-European Transmission. IEEE Power and Energy Magazine, Vol.12, Issue 2, March-April 2014

[14] IEA (2016) Large-scale electricity interconnection - Technology and prospects for cross-regional networks, Paris

[15] Al-Asaad HK (2009) Electricity Power Sector Reform in the GCC Region. The Electricity Journal, 22(9): 58-64

[16] Ardelean M, Minnebo P (2015) JRC technical reports; HVDC Submarine Power Cables in the World; State-of-the-Art Knowledge

[17] Chen G, Hao M, Xu Z et al (2015) Review of high voltage direct current cables. CSEE Journal of Power and Energy Systems, 1(2): 9-21

[18] Barnes M, Hertem D Van, Teeuwsen SP, et al (2017) HVDC Systems in Smart Grids, Proceedings of the IEEE 105(11): 2082-2098

[19] Kangwa N, Venugopal C, Davidson I (2017) A Review of the Performance of VSC-HVDC and MTDC Systems. In: 2017 IEEE PES-IAS PowerAfrica. IEEE, pp: 267-273

[20] Qin X, Zeng P, Zhou Q, et al (2016) Study on the Development and Reliability of HVDC Transmission Systems in China. In: 2016 IEEE International Conference on Power System Technology (POWERCON). IEEE, pp: 1-6

[21] Sutton SJ, Lewin PL, Swingler SG (2017) Review of global HVDC subsea cable projects and the application of sea electrodes. International Journal of Electrical Power and Energy Systems, Vol.87, pp: 121-135

[22] Ardelean M, Minnebo P (2017) JRC science for policy report; A China-EU electricity transmission link; Assessment of potential countries and routes, Petten

[23] EC (2016) EuroAsia Interconnector - Design, Implementation and Environmental Studies, Brussels

[24] Blakers A, Luther J, Nadolny A (2012) Asia Pacific Super Grid - Solar electricity generation, storage and distribution. Green, 2(4): 189-202

[25] Chatzivasileiadis S, Ernst D, Andersson G (2013) The Global Grid. Renewable Energy, 57: 372-383

[26] Czisch G (2008) Low Cost but Totally Renewable Electricity Supply for a Huge Supply Area - a European/Trans-European Example -. In: 4th CLAVERTON ENERGY GROUP CONFERENCE -, 24th to 26th October 2008, Bath

[27] IEA (2016) World Energy Outlook 2016, Paris

[28] Liu Z (2015) Global Energy Interconnection. Elsevier Academic Press

[29] Biberacher M (2004) Modelling and optimisation of future energy system using spatial and temporal methods, Dissertation, University of Augsburg

[30] Aboumahboub T, Schaber K, Tzscheutschler P et al (2010) Optimization of the Utilization of Renewable Energy Sources in the Electricity Sector. In: EE'10 Proceedings of the 5th IASME/WSEAS international conference on Energy & environment, World Scientific and Engineering Academy and Society (WSEAS), Wisconsin, pp: 196-204

[31] Aboumahboub T, Schaber K, Wagner U et al (2012) On the CO_2 emissions of the global electricity supply sector and the influence of renewable power-modeling and optimization. Energy Policy, 42(C): 297-314

[32] Dekker P-M, Meisen P, Bruton AB (1995) THE GENI MODEL: The Interconnection of Global Power Resources to Obtain an Optimal Global Sustainable Energy Solution. SIMULATION, 64(4): 244-253

[33] Ummel K(2010) Global Prospects for Utility-Scale Solar Power : Toward Spatially Explicit Modeling of Renewable Energy

Systems. Center for Global Development Working Paper. No. 235, December 2010
[34] Energy Exemplar (2018). https://energyexemplar.com/. Accessed 5 May 2018
[35] EC (2016) EU Reference Scenario 2016; Energy, transport and GHG emissions - Trends to 2050, Brussels
[36] EIA (2017) The Electricity Market Module of the National Energy Modeling System : Model Documentation 2016, Washington DC
[37] EIA (2017) Annual Energy Outlook 2017, Washington DC
[38] EIA (2017) Annual Energy Outlook 2017; Electricity and Renewable fuel tables (tables 55-58.22). https://www.eia.gov/outlooks/archive/aeo17/supplement/excel/sup_elec.xlsx. Accessed 14 Feb. 2018
[39] FERC (2017) Form No. 714 - Annual Electric Balancing Authority Area and Planning Area Report. https://www.ferc.gov/docs-filing/forms/form-714/data/form714-database.zip. Accessed 10 Nov. 2017
[40] EIA (2018) U.S. Electric System Operating Data; Status Map. https://www.eia.gov/realtime_grid/#/status?end=20170905T00. Accessed 17 Nov. 2017
[41] FERC (2017) Electric Power Markets: National Overview. https://www.ferc.gov/market-oversight/mkt-electric/overview.asp. Accessed 17 Nov. 2017
[42] EIA (2018) API Query Browser. https://www.eia.gov/opendata/qb.php?category=2122632. Accessed 24 Nov. 2017
[43] National Energy Board of Canada (2017) Canada's Energy Future 2017; Energy Supply and Demand Projections to 2040. Calgary
[44] Nova Scotia Power (2018) Hourly total net Nova Scotia load. http://oasis.nspower.ca/en/home/oasis/monthly-reports/hourly-total-net-nova-scotia-load.aspx. Accessed 20 Dec. 2017
[45] NB Power (2018) System Information Archive. https://tso.nbpower.com/Public/en/system_information_archive.aspx. Accessed 20 Dec. 2017
[46] IESO (2018) Data Directory. http://www.ieso.ca/en/power-data/data-directory. Accessed 20 Dec. 2017
[47] AESO (2016) 2016 hourly load data. https://www.aeso.ca/market/market-and-system-reporting/data-requests/2016-hourly-load-data/. Accessed 20 Dec. 2017
[48] BC Hydro (2018) Historical Transmission Data; LOAD: British Columbia. https://www.bchydro.com/energy-in-bc/operations/transmission/transmission-system/balancing-authority-load-data/historical-transmission-data.html. Accessed 20 Dec. 2017
[49] Pfenninger S, Staffell I (2016) Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy, Vol. 114, pp:1251-1265
[50] Staffell I, Pfenninger S (2016) Using bias-corrected reanalysis to simulate current and future wind power output. Energy. Vol. 114, pp: 1224-1239
[51] Purvins A, Sereno L, Ardelean M et al (2018) Submarine power cable between Europe and North America: A techno-economic analysis. Journal of Cleaner Production, Vol. 186, pp.: 131-145
[52] Chatzivasileiadis S, Ernst D (2017) The State of Play in Cross-Border Electricity Trade and the Challenges towards a Global Electricity Market Environment. In: International Trade in Sustainable Electricity: Regulatory Challenges in International Economic Law. Cambridge, pp: 21-45
[53] Gellings CW (2015) A Globe-Spanning Supergrid. IEEE Spectrum, 52(8):48-54
[54] AEMO (2018) DATA DASHBOARD. https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Data-dashboard#aggregated-data. Accessed 19 Dec. 2017
[55] Mininistry of Economy Trade and Industry Japan (2011) Past power demand record (Translated). http://www.meti.go.jp/setsuden/performance.html. Accessed 19 Dec. 2017
[56] Secretariat of Energy Mexico (2017) Programa de Desarrollo del Sistema Eléctrico Nacional; base de datos de demanda horaria. http://base.energia.gob.mx/prodesen/PRODESEN2016/DemandaHoraria.xlsx. Accessed 22 Dec. 2017
[57] SO-CDU UES (2018) Generation and consumption (hours) (Translated). http://www.so-cdu.ru/index.php?id=972&tx_ms1cdu_pi1%5Bkpo%5D=1019&tx_ms1cdu_pi1%5Bdt%5D=01.01.2015. Accessed 19 Dec. 2017
[58] Byers L, Friedrich J, Hennig R et al (2018) A Global Database of Power Plants
[59] Medjroubi W, Müller UP, Scharf M, et al (2017) Open Data in Power Grid Modelling: New Approaches Towards Transparent Grid Models. Energy Reports, Vol.3 pp:14-21
[60] Liang X (2018) Application and research of global grid database design based on geographic information. Global Energy Interconnection, 1(1): 87-95

Biographies

Maarten Brinkerink obtained his master degree in energy and environmental sciences in 2017 from the University of Groningen, the Netherlands. He is currently working as a Ph.D. researcher within the MaREI Centre in University College Cork, Ireland. His research interests lie in energy- and power system modelling, electricity markets and renewables integration. Current focus Of not on Maarten's Ph.D. centres around the dispatch modelling of a global interconnected power system model.

Dr. Paul Deane is a research fellow specializing in energy and climate policy with the MaREI Centre in University College Cork. His research activities include integrated energy systems modelling to assess whole system pathways and policies to low carbon futures. Paul is a member of a number of European multidisciplinary think-tanks and scientific advisor to a number of European energy projects. He is an active contributor to European policy thinking on renewable energy.

Seán Collins is a Science Foundation Ireland (SFI) funded, Ph.D. researcher of the MaREI Centre. His research interests focus on enabling improved scenario analysis for power systems in Ireland and the EU-28. This involves dispatch modelling and analysis of the European power system under various levels of decarbonisation ambition to provide insights relevant to the development of European energy policy.

Prof. Brian Ó Gallachóir is Professor of Energy Engineering in University College Cork and Vice-Director of UCC's Environmental Research Institute. He is also Director of the national SFI MaREI Centre, a £48M energy and marine-based research, development and innovation hub based in Ireland with 200 researchers and 48 industry partners. Brian is also elected Chair of IEA's Technology Collaboration Programme on energy systems modelling (IEA-ETSAP). Brian is a member of the Irish Government's Technical Research and Modelling (TRAM) Working Group on energy and climate mitigation.

(Editor Zhou Zhou)